

***DESIGN AND QUALITY
ASSESSMENT OF FORWARD
AND INVERSE ERROR
DIFFUSION HALFTONING
ALGORITHMS***

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OUTLINE

- Introduction to halftoning and JBIG2
- Perceptually weighted SNR measure
- Halftoning by error diffusion
 - Linear gain model
 - Modified error diffusion
 - Noise metric
 - Tonality metric
- Inverse halftoning
 - Algorithm design and results
 - Modeling inverse halftoning
 - Quality metrics
- Interpolation and rehalftoning
- Conclusions

INTRODUCTION: HALFTONING

- Was analog, now digital processing
- Wordlength reduction for images
 - ▶ 8-bit to 1-bit for grayscale
 - ▶ 24-bit RGB to 8-bit for color displays
 - ▶ 24-bit RGB to CMYK for color printers
- Applications
 - ▶ Printers
 - ▶ Digital copiers
 - ▶ Liquid crystal displays
 - ▶ Video cards
- Halftoning methods
 - ▶ Screening
 - ▶ Error diffusion
 - ▶ Direct binary search
 - ▶ Hybrids

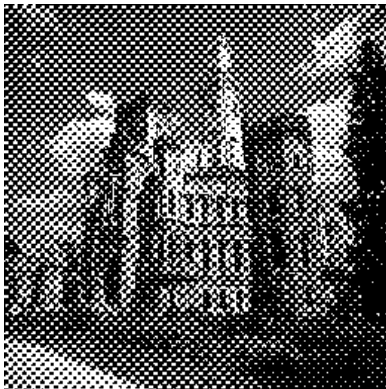
EXAMPLE HALFTONES



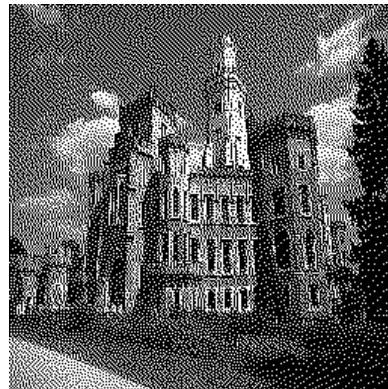
Original image



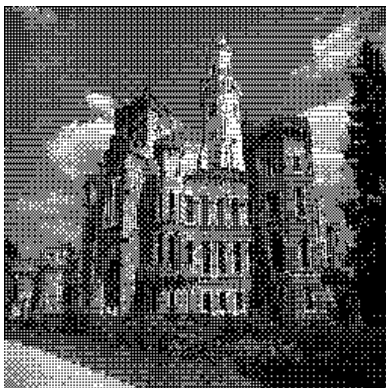
Direct binary search



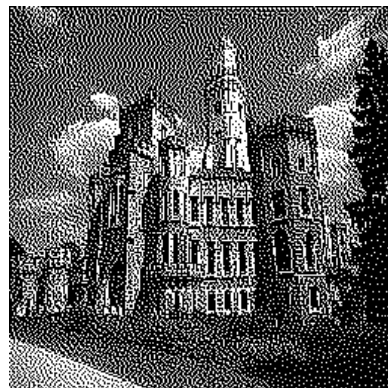
Clustered dot screen



Error diffusion I

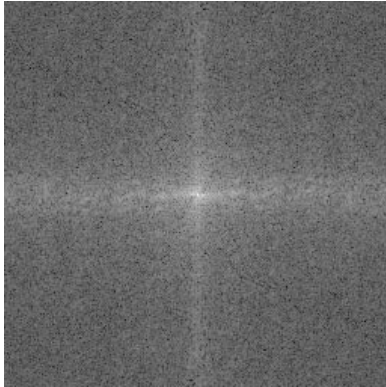


Dispersed dot screen

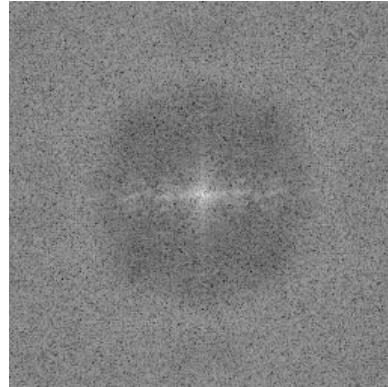


Error diffusion II

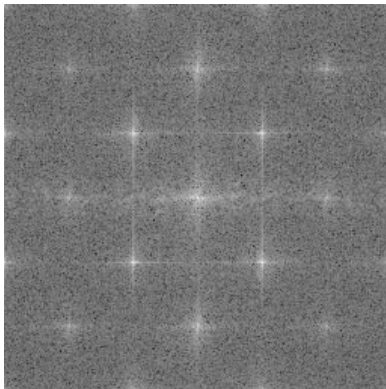
FOURIER TRANSFORMS



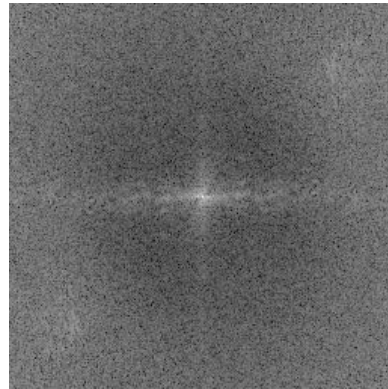
Original image



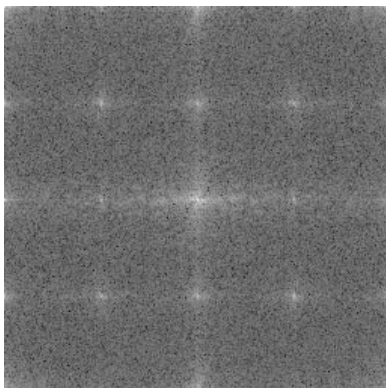
Direct binary search



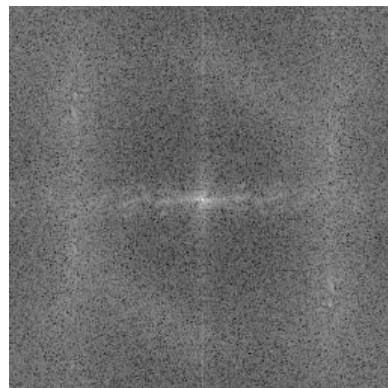
Clustered dot screen



Error diffusion I



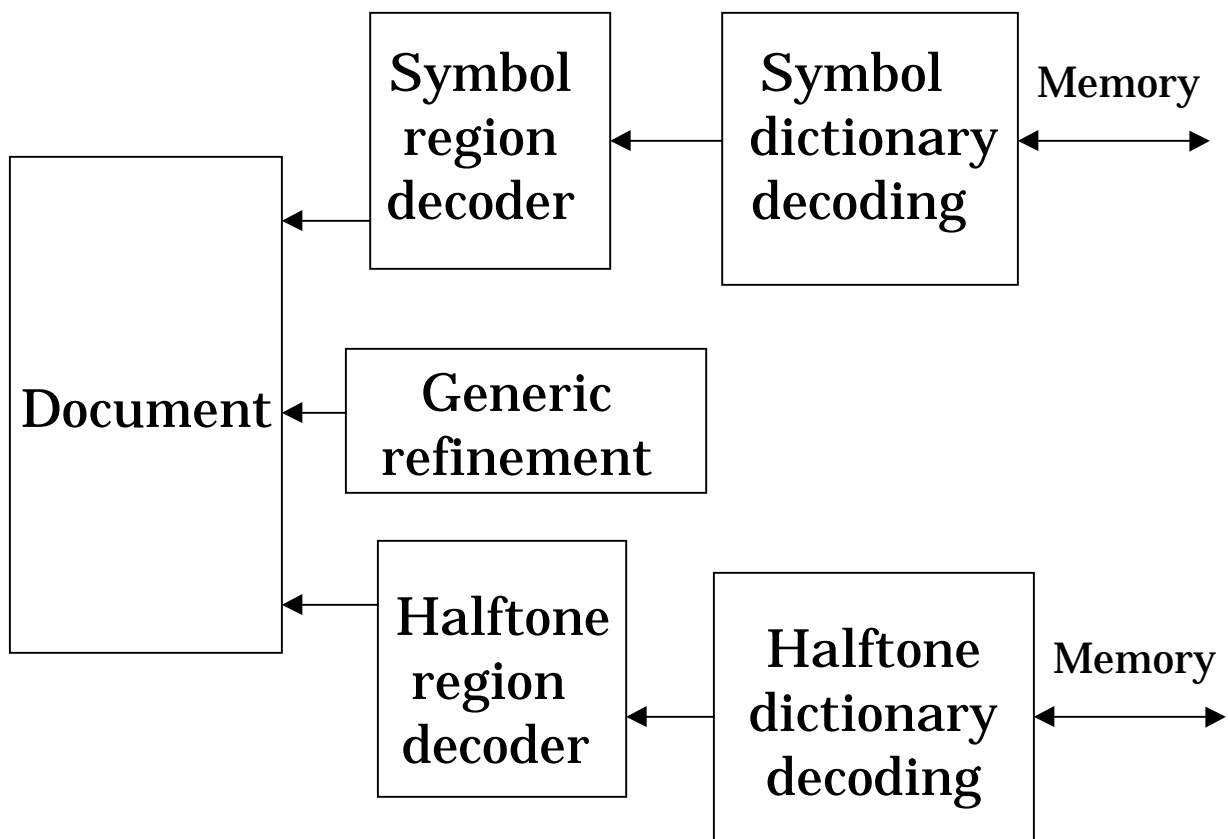
Dispersed dot screen



Error diffusion II

THE JBIG2 STANDARD

- Lossy/lossless coding of bi-level text and halftone data



- Scan vs. random mode

THE JBIG2 STANDARD (cont.)

- **Bi-level text coding**
 - ▶ Hard pattern matching (lossy)
 - ▶ Soft pattern matching (lossless or near lossless) may be context based
- **Halftone coding**
 - ▶ Direct halftone compression
 - ▶ Context based halftone coding
 - ▶ Inverse halftoning and compression of grayscale image
- **Implications**
 - ▶ Printers, fax machines, scanners, etc. will need to decode JBIG2 bitstreams
 - ▶ Fast decoding may require dedicated hardware and embedded software
 - ▶ Need for low complexity, low memory solutions

PROBLEMS TO BE SOLVED

- Visual quality metrics for forward and inverse halftones
 - ▶ Quantify frequency distortion
 - ▶ Quantify effect of scan
 - ▶ Quantify quantization noise
- Modeling error diffusion
 - ▶ Develop tractable model
 - ▶ Demonstrate accuracy of model
 - ▶ Use model to improve designs
- Inverse halftoning
 - ▶ Develop efficient algorithm
 - ▶ Develop model for inverse halftoning
 - ▶ Fast JBIG2-compliant rehalftoning

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HUMAN VISUAL SYSTEM

- Non-linear, spatially varying
- Assuming spatial invariance and linearity explains [Cornsweet 1970]
 - Mach band effect (false edge sharpness)
 - Apparent brightness vs. intensity



White noise
SNR = 10 dB

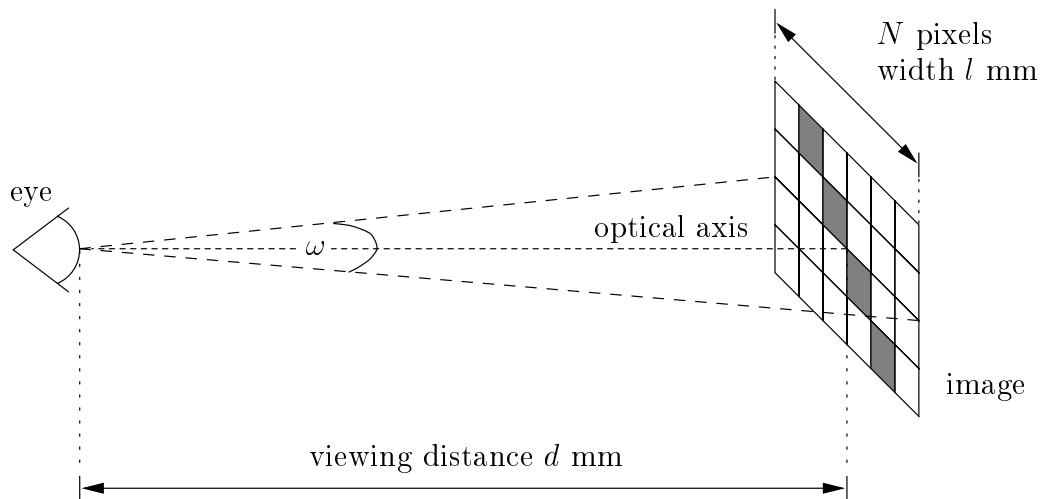


Blue (highpass) noise
SNR = 10 dB

- Weight noise component by spatial frequency to quantify visual impact

ANGULAR FREQUENCY

- Sensitivity depends on angular frequency subtended at eye
- Compute angular frequency from image size (pixels), printed image size (mm), viewing distance (mm)



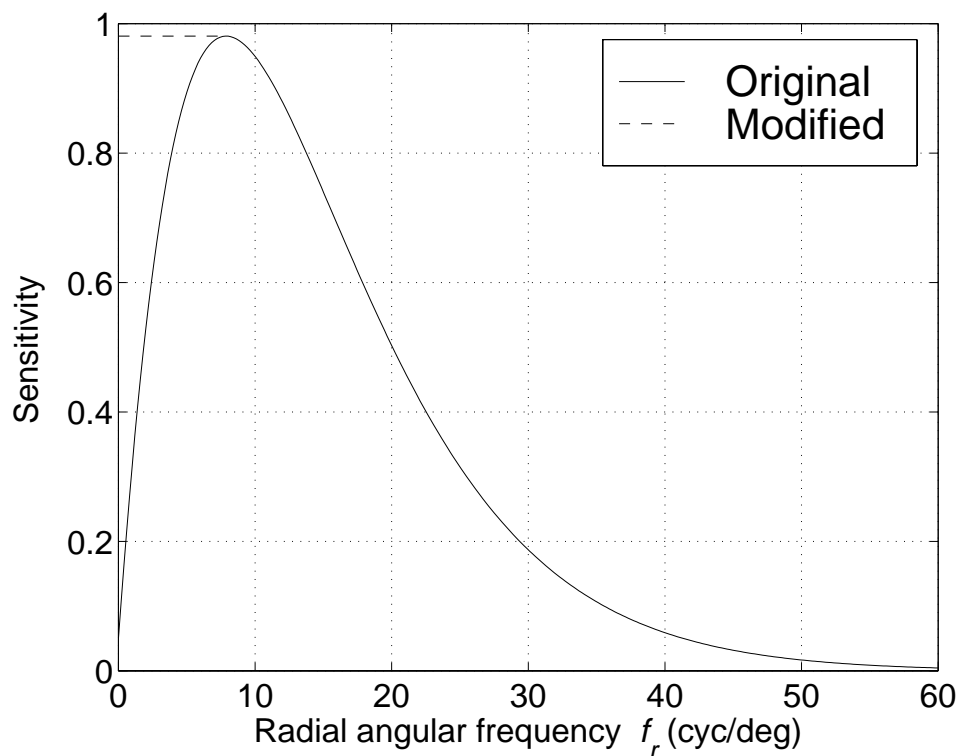
- At Nyquist frequency

$$f_a = \frac{N\pi d}{360l} \text{ cycles/degree}$$

CONTRAST SENSITIVITY (CSF)

- Minimum contrast to distinguish sine grating from uniform field
- Model [Mannos & Sakrison 1974]
- Modification [Mitsa & Varkur 1993]

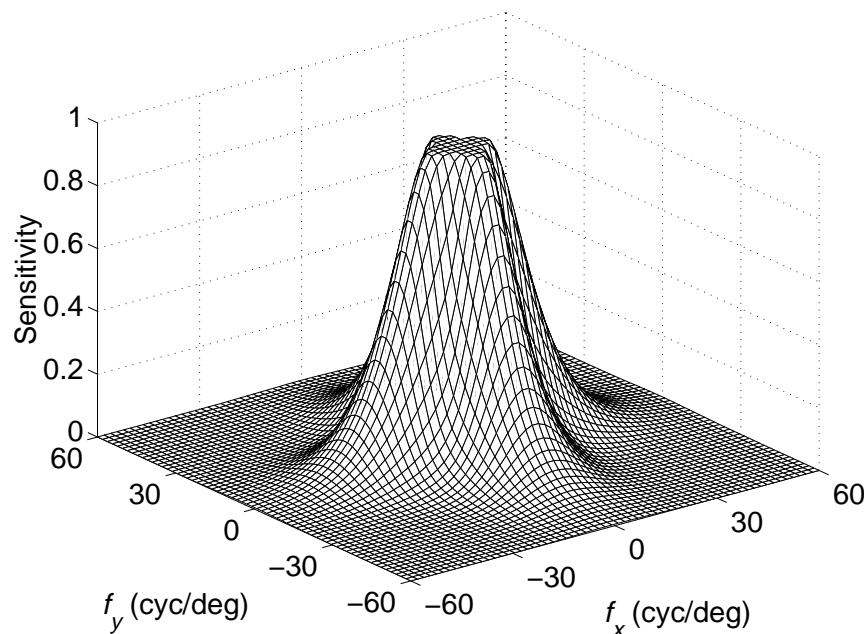
$$CSF = 2.6 (0.02 + 0.1 f_a) e^{-(0.1 f_a)^{1.1}}$$



- Orientation-independent

WEIGHTED SNR MEASURE

- Include angular dependence (orientation) in CSF
[Sullivan, Miller & Pios 1993]

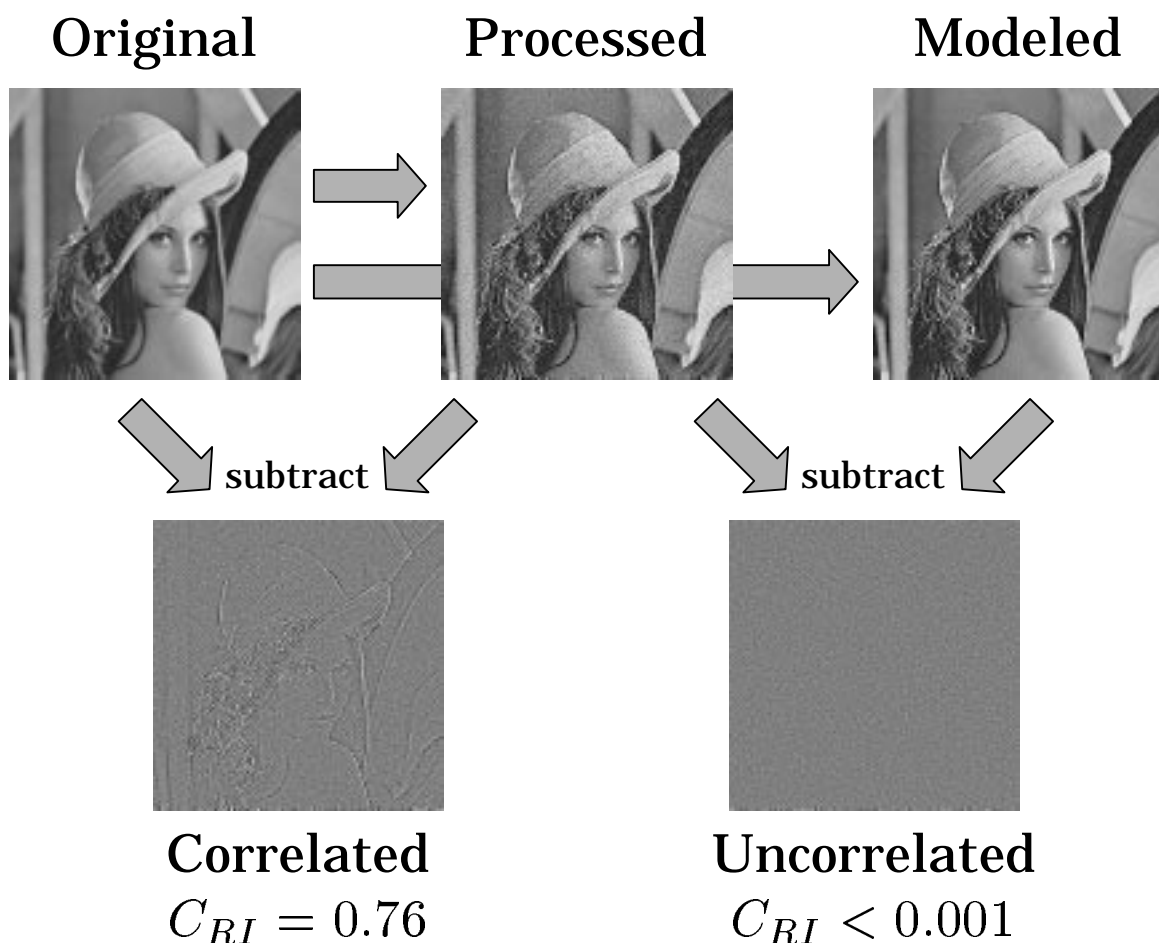


- Compute weighted signal-to-noise ratio between original image x and processed image y by $\text{CSF}(u, v)$

$$\text{WSNR} = 10 \log_{10} \left(\frac{\sum |\text{CSF} \times X(u, v)|^2}{\sum |\text{CSF} \times (X(u, v) - Y(u, v))|^2} \right)$$

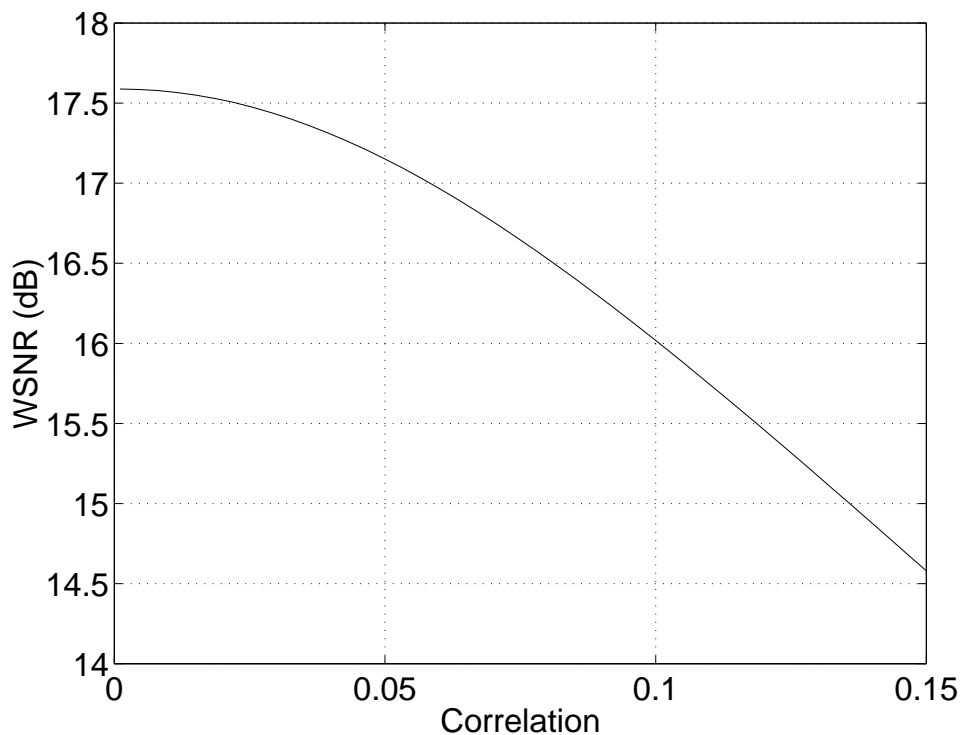
MODELING DISTORTION

- SNR measures assume *uncorrelated additive noise*
 - Difference (residual) between original and processed image must be uncorrelated: $C_{RI} < 0.020$
 - Compensate for other distortions



WSNR vs. CORRELATION

- Accuracy of SNR measures decrease as amount of correlation increases

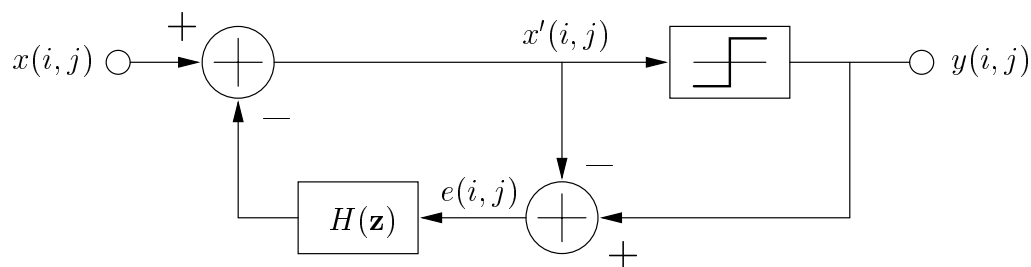


OUTLINE

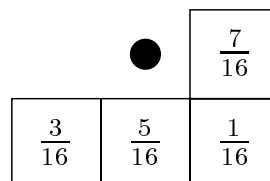
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ERROR DIFFUSION

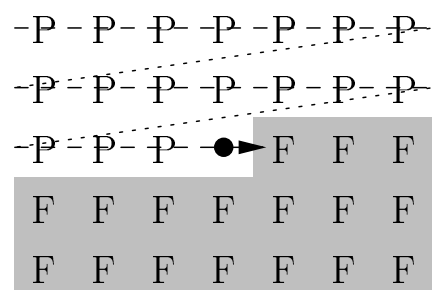
- 2-D delta-sigma modulator
- Noise shaping feedback coder



- Error filter



- Raster scan order



P = Past
F = Future

- Serpentine scan also used

ERROR DIFFUSION (contd.)

- **Quantizer**

$$y(i, j) = \begin{cases} 0, & x'(i, j) < 0.5 \\ 1, & x'(i, j) \geq 0.5 \end{cases}$$

- **Governing equations**

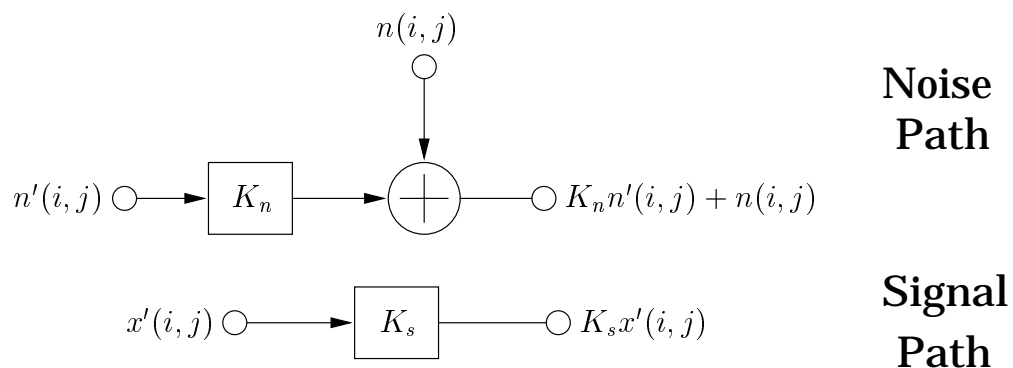
$$e(i, j) = y(i, j) - x'(i, j)$$

$$x'(i, j) = x(i, j) - h(i, j) * e(i, j)$$

- **Non-linearity difficult to analyze**

- **Linearize quantizer**

[Kite, Evans, Bovik & Sculley 1997]



- **Separate signal and noise paths**

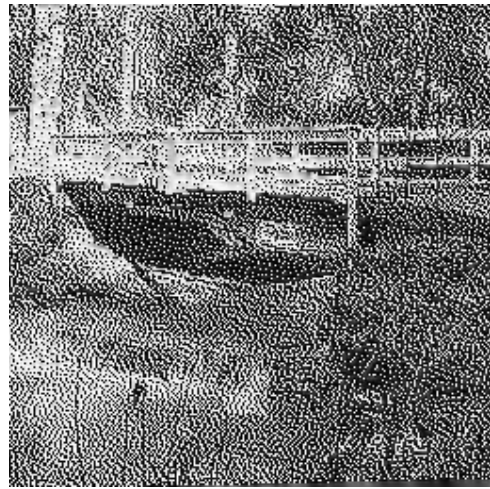
[Ardalan & Paulos 1987]

LINEAR GAIN MODEL

- Quantization error correlated with input [Knox 1992]



Floyd-Steinberg



Jarvis, Judice & Ninke

- Least squares fit of quantizer input to output defines signal gain

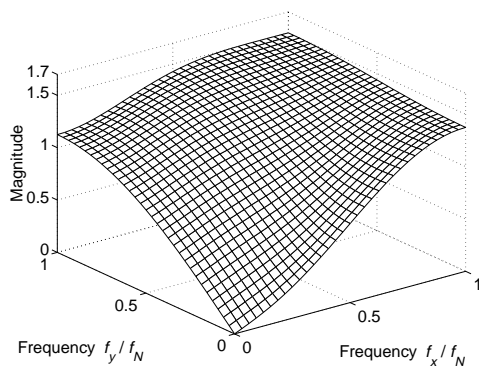
$$K_s = \frac{E[|x'(i, j)|]}{2E[x'(i, j)^2]}$$

- Signal gain: $K_s \approx \text{constant}$
- Noise gain: $K_n = 1$

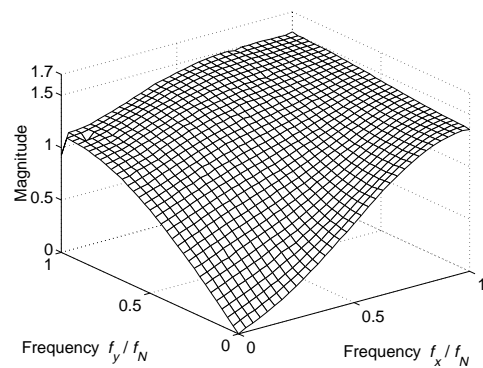
GAIN MODEL PREDICTIONS

■ Noise transfer function (NTF)

$$\text{NTF} = 1 - H(\mathbf{z})$$



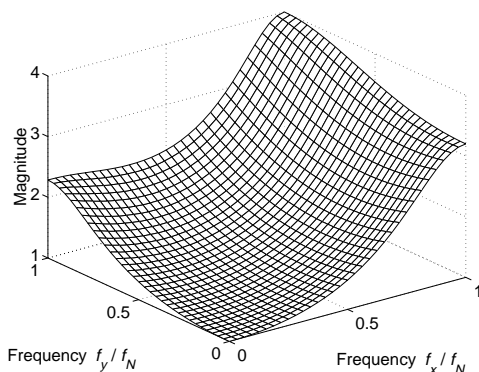
Predicted



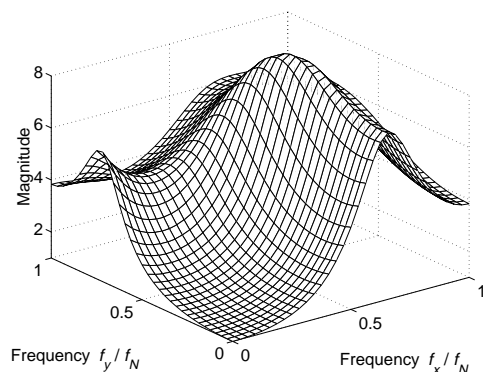
Measured

■ Signal transfer function (STF)

$$\text{STF} = \frac{K_s}{1 + (K_s - 1)H(\mathbf{z})}$$



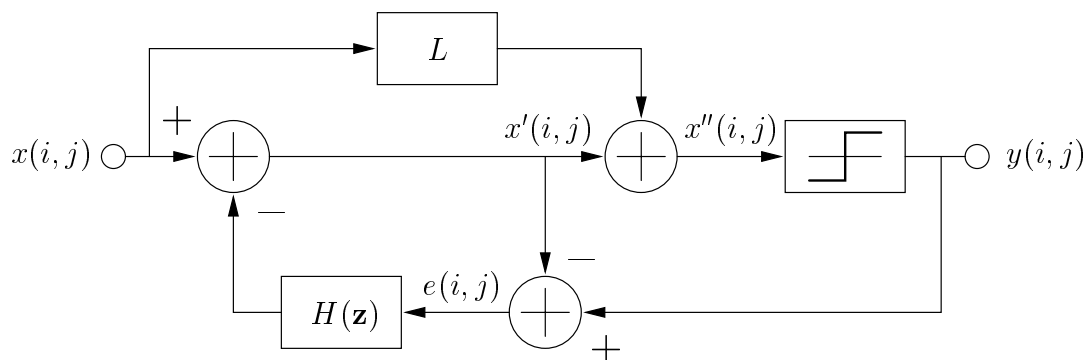
Floyd-Steinberg



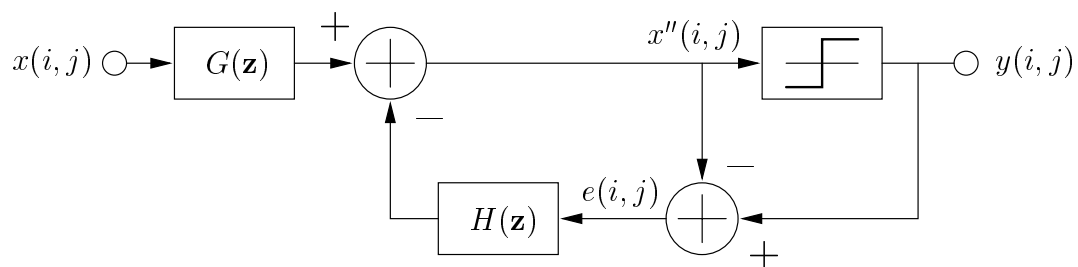
Jarvis *et al.*

MODIFIED ERROR DIFFUSION

- Efficient method of adjusting sharpness [Eschbach & Knox 1991]



- Equivalent circuit: pre-filter



$$G(z) = 1 + L(1 - H(z))$$

UNSHARPENED HALFTONES

- If $L = \frac{1 - K_s}{K_s}$ then STF = 1 (flat)
- Accounts for frequency distortion



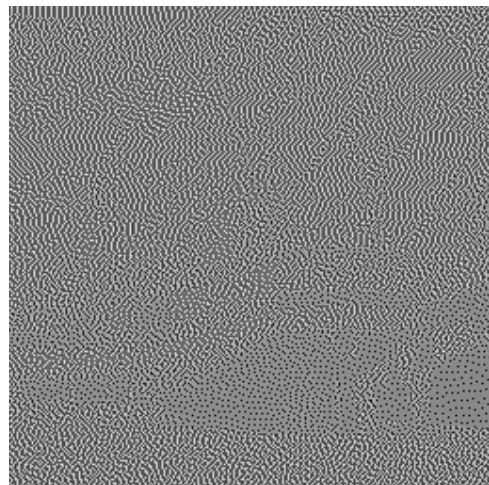
Original image



Jarvis halftone



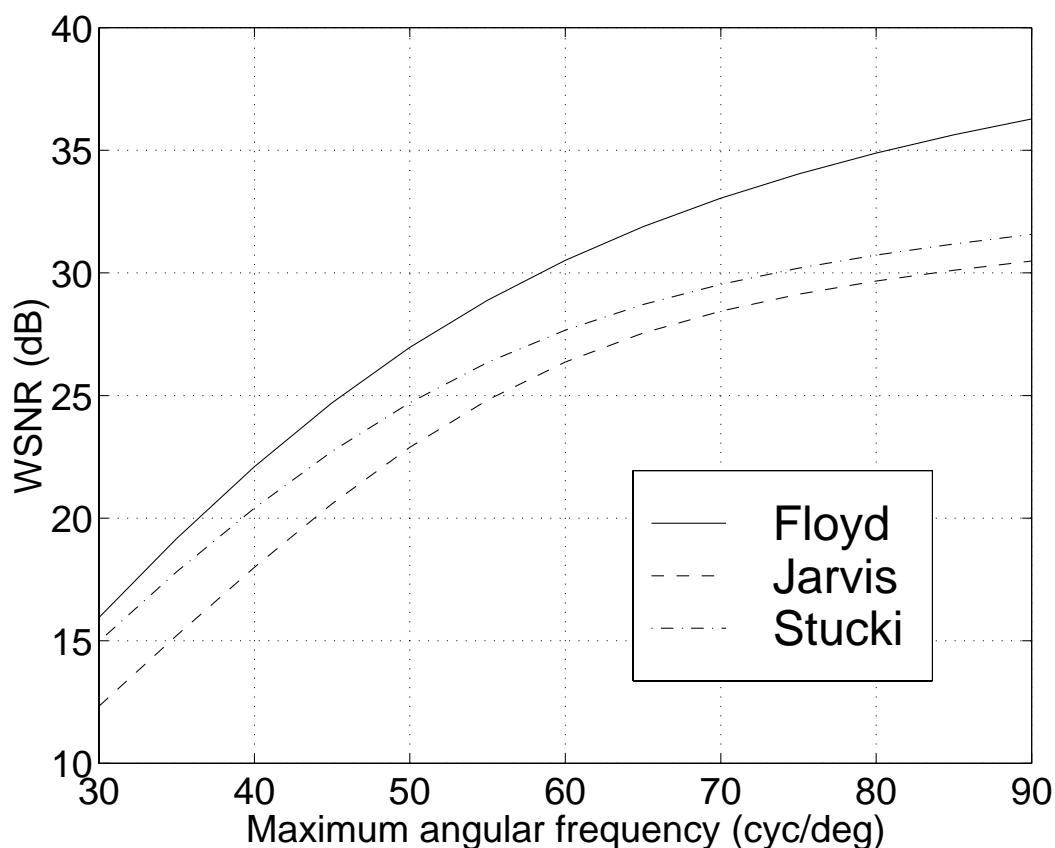
Unsharpened halftone



Residual

OBJECTIVE NOISE METRIC

- To find WSNR
 - ▶ Compute signal gain K_s , or use average
 - ▶ Generate unsharpened halftone using modified error diffusion
 - ▶ Compute WSNR of unsharpened halftone relative to original image



OBJECTIVE TONALITY METRIC

- Limit cycles cause visual ‘worm’ artifacts [Fan & Eschbach 1994]
- Larger filters and serpentine scan result in lower tonality
- Define tonality metric
 - ▶ Total distortion of sine grating

$$T = \left[\frac{1}{Y(e^{j\omega_f})Y^*(e^{j\omega_f})} \sum_{\omega \in \{\omega_d\}} Y(e^{j\omega})Y^*(e^{j\omega}) \right]^{\frac{1}{2}}$$

- ▶ ω_f is the grating frequency
 - ▶ Average T over tone frequencies $\{\omega_d\}$: harmonics and aliased harmonics of ω_f
- Agrees with subjective evaluation
 - ▶ Correct ranking of error filters
 - ▶ Serpentine scan less tonal

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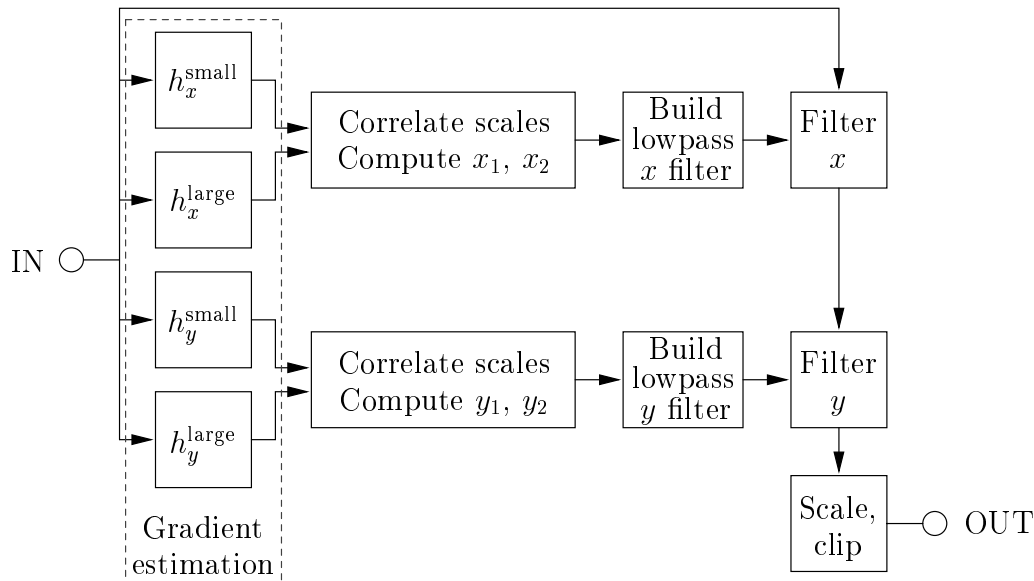
INVERSE HALFTONING

- Recover grayscale from halftones
- Applications
 - Digital copiers (could support JBIG2)
 - Scanner software (could support JBIG2)
 - Embedded JBIG2 decoders
- Frame-based approaches
 - Bayesian estimation
 - Projection onto convex sets
 - Iterative lowpass smoothing and nonlinear filtering
 - Wavelet denoising
- Scan-based approaches
 - Proposed fast algorithm
- Frame-based methods are slow, memory-hungry, and often iterative

PROPOSED METHOD

- **Apply anisotropic diffusion**
[Kite, Damera-Venkata, Evans & Bovik 1998]
 - ▶ Estimate image gradients
 - ▶ Compute diffusion coefficient
 - ▶ Preserve edges, smooth elsewhere
- **Unique environment**
 - ▶ Highpass noise, SNR \approx 3 dB
 - ▶ Tonal
- **Solution**
 - ▶ Specialized gradient estimator
 - ▶ Correlate estimate across scales
[Mallat & Zhong 1992]
 - ▶ Separable — smooth parallel to edges
- **Local operations**
 - ▶ Low memory requirement
 - ▶ Low computational cost

PROPOSED METHOD (cont.)

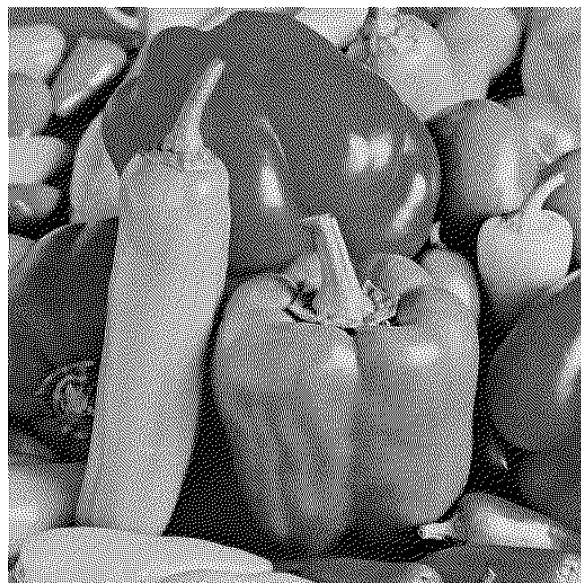


- Estimate gradients at two scales
 - 7×7 and 5×5 FIR filters
 - Integer additions only
- Correlate gradients across scales
 - 5 dB improvement in gradient SNR
- Build parametric smoothing filter
 - 7×7 separable FIR filter
 - Family optimized for halftones
 - Quantized integer coefficients

INVERSE HALFTONE RESULTS



Original image



Halftone



Proposed method, 3s



Wavelet method, 180s

INVERSE HALFTONING MODEL

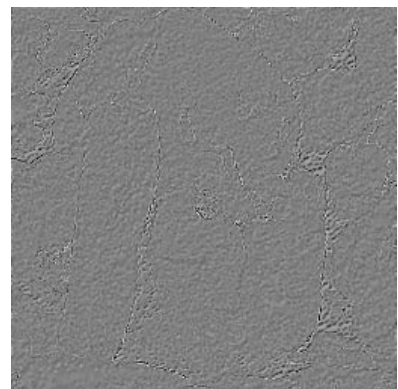
- Inverse (forward) halftoning blurs (sharpens) image and adds noise
- Model inverse halftoning
 - Compute unsharpened halftone
 - Inverse halftone; save filter parameters at each pixel
 - Filter original image using saved filters
- Typical correlation
 - Inverse halftone: $C_{RI} = 0.32$
 - Modeled inverse halftone: $C_{RI} = 0.01$



Inverse halftone



Modeled



Residual ($\times 4$)

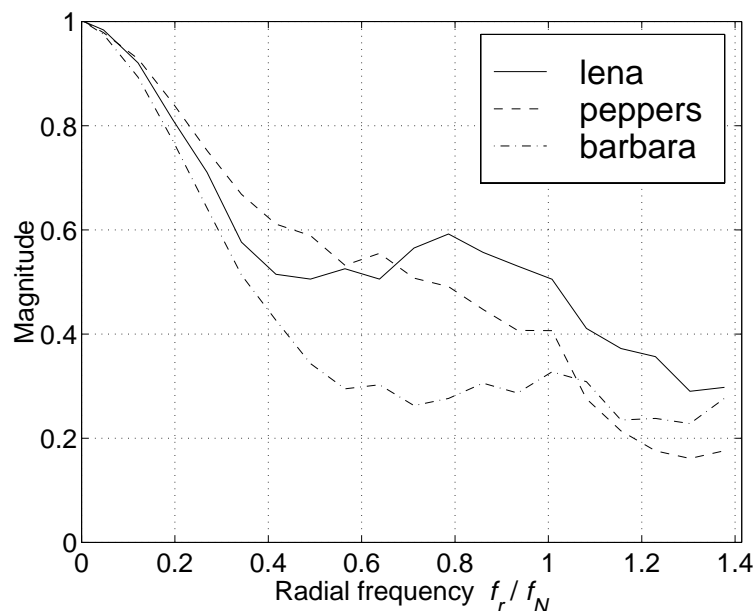
INVERSE HALFTONE QUALITY

■ WSNR results

Reference Image	WSNR(dB)				
	<i>boats</i>	<i>lena</i>	<i>barbara</i>	<i>mandrill</i>	<i>peppers</i>
Original	25.36	26.93	20.47	19.02	27.69
Model	33.02	32.74	32.29	31.93	31.77

■ Compute effective transfer function

- ▶ Divide FFT of model inverse halftone by FFT of original image
- ▶ Radially average over annuli
- ▶ Lowpass characteristic (blurring effects)



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INTERPOLATION

- Image resizing
- Different methods (increasing cost)
 - ▶ Nearest neighbor
 - ▶ Bilinear
 - ▶ Bicubic, cubic splines, lowpass filtering
- Nearest neighbor, bilinear methods
 - ▶ Low computational cost
 - ▶ Artifacts masked by quantization noise in halftone
 - ▶ Correct blurring by modified error diffusion
- Examine $\times 2$ interpolation: method applies to any scaling factor
- Design L for flat transfer function using linear gain model (L is constant for given interpolator)

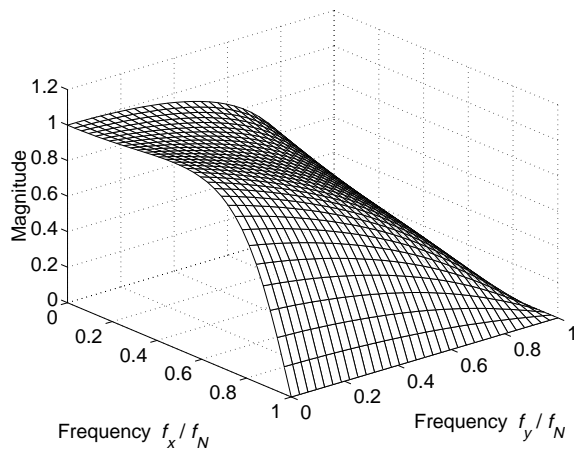
INTERPOLATION RESULTS



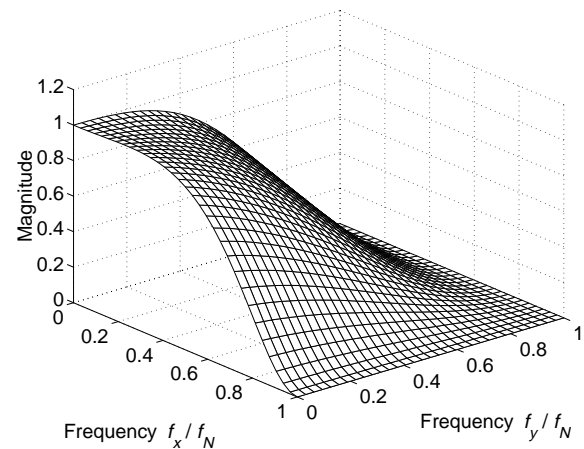
Nearest neighbor $\times 2$



Bilinear $\times 2$



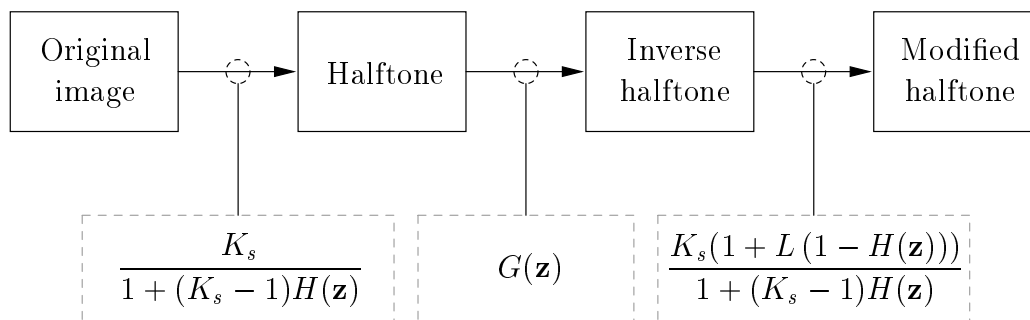
Transfer function
 $L = -0.0105$



Transfer function
 $L = 0.340$

REHALFTONING

- Halftone conversion, manipulation
- Error diffused halftones
- Fixed lowpass inverse halftoning filter, compromise cut-off frequency
 - Noise leakage masked by halftoning
 - Correct blur by modified error diffusion
 - Computationally efficient



- Use linear gain model to design L for flat response
- Use approximation for digital frequency: $e^{j\omega} \approx 1 + j\omega - \omega^2/2$

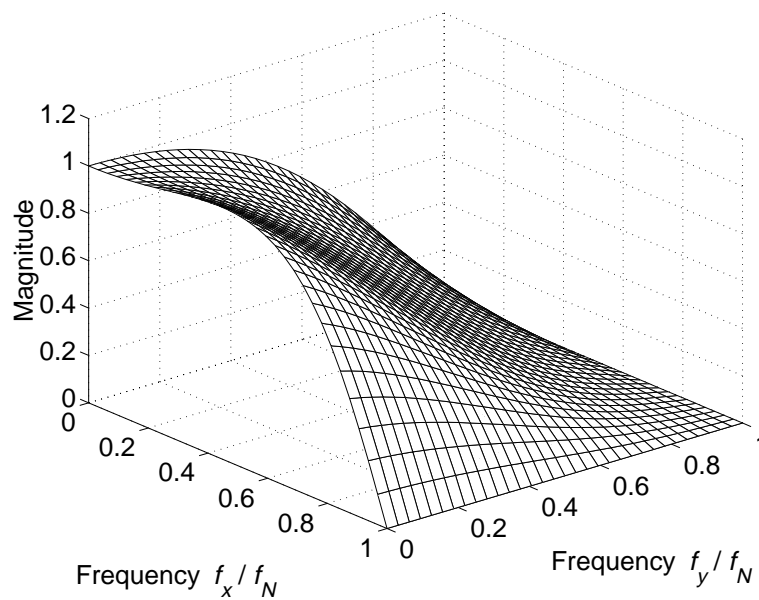
REHALFTONING RESULTS



Original image



Rehalthtone



Signal transfer function

IMPLICATIONS FOR JBIG2

- **JBIG2 embedded decoders**
 - ▶ Low memory requirements
 - ▶ Low computational complexity
 - ▶ High parallelism
- **Inverse halftoning: a robust solution for lossy coding of halftones**
 - ▶ Rendering device can use a different halftoning scheme than encoder
 - ▶ Multiresolution halftone rendering (archive browsing)
 - ▶ High halftone compression ratios (9-16:1)
 - ▶ Quality enhancement if the encoder halftoning method is transmitted
- **Low-cost embedded implementations**

CONCLUSIONS

- Visual quality measures for distortion and noise in halftones
- Linear gain model of error diffusion
 - Validate accuracy of quantizer model
 - Tonality measure accounts for artifacts
 - Link between filter gain and signal gain
- Inverse halftoning
 - New efficient method, embedded
 - Model inverse halftoning
 - Quality measures for inverse halftones
- Rehalftoning and interpolation
 - Efficient algorithms
 - Impact on emerging JBIG2 standard
- Web site for software and papers
 - <http://www.ece.utexas.edu/~bevans/projects/inverseHalftoning.html>